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TO EXPLORE THE 1 TEV SCALE

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ABSTRACT

I summarize the case for new physics at the TeV scale, and review speculations about new phenomena which may occur there. I then discuss the physics prospects of a multi-TeV hadron collider, and examine some of the processes which may be studied in detail with such an instrument.

1 INTRODUCTION

A great deal has happened since the first Vanderbilt Conference in 1973. At Vanderbilt, the high-energy physics group has grown in numbers and in influence, and the department has even taken the radical step of hiring two new theorists! In physics itself, the changes have been no less dramatic. At the time of the 1973 Conference, many of the things we now take for granted as basic elements of our world-view had not yet been established. Quarks and color were still regarded as vaguely subversive ideas. The formulation of QCD awaited the recognition of asymptotic freedom. Neutral currents had not yet been discovered. Large-$p_\perp$ pions had been observed, but jets of hadrons had not yet made their experimental appearance. Neither the ψ/J nor charmed particles had been found. The Drell-Yan mechanism was viewed with deep suspicion. The remarkable progress of these thirteen years, marked by experimental discovery, theoretical insight, and instrumental innovation in abundant measure, has led us to a radically new, simple, and far-reaching conception of Nature, which we call The Standard Model.

The Standard Model is shown schematically in Fig. 1. It is, at least at first sight, a scheme of considerable economy. We have identified a small number of fundamental constituents, the quarks and leptons, and have recognized that the elementary interactions among them all may be described by gauge theo-

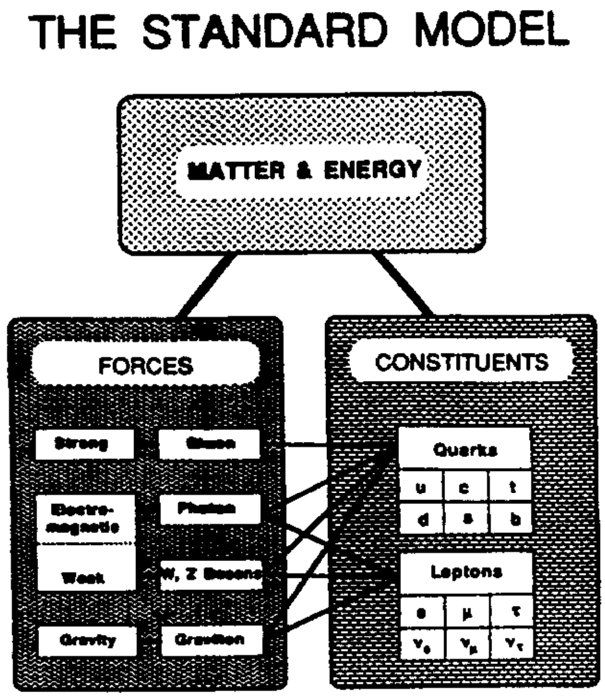


Figure 1: The Standard Model of Particle Physics.

ries. The picture has a pleasing degree of coherence, and holds the promise of deeper understanding – in the form of a further unification of the elementary interactions – still to come.

This is an accomplishment worthy of the pleasure we take in it, but if we have come impressively far since the first Vanderbilt Conference, we still have quite far to go. The very success of the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model prompts new questions:

- Why does it work?
- Can it be complete?
- Where will it fail?

The standard model itself hints that the frontier of our ignorance lies at ~ 1 TeV for collisions among the fundamental constituents. In more general terms, the success of our theoretical framework suggests that a significant step beyond present-day energies is needed, to see breakdowns of the theory.

Beyond these generalities, there are many specific issues to be faced. There is, for example, our incomplete understanding of electroweak symmetry breaking and the suggestion (from the "bound" $M_{\rm Higgs} < 1\ {\rm TeV}/c^2$, for example) that the 1 TeV scale will be crucial to a resolution of this problem. The Higgs mechanism provides a means for generating quark and lepton masses and mixing angles, but leaves the values as free parameters. We do not understand what CP-violation means. The idea of quark-lepton generations is suggested by the necessity for anomaly cancellation in the electroweak theory, but the *meaning* of generations is unclear. We may even dare[1] to ask what is the origin of the gauge symmetries themselves. Such questions – and this is but a partial list – are stimulated by the standard model itself, and by our desire to find ever simpler descriptions of Nature, of ever more general applicability.

Beyond our search for more complete understanding, there are many reasons to be dissatisfied with the standard model. A powerful aesthetic objection is raised by the arbitrariness of the theory, which requires us to specify a multitude of apparently free parameters:

- 3 coupling parameters α_s, α_{EM}, and $\sin^2\theta_W$,
- 6 quark masses,
- 3 generalized Cabibbo angles,
- 1 CP-violating phase,
- 2 parameters of the Higgs potential,
- 3 charged lepton masses,
- 1 vacuum phase angle,

for a total of 19 arbitrary parameters. A similar count holds for the known examples of unified theories of the strong, weak, and electromagnetic interactions, such as $SU(5)$.

2 WHY THERE MUST BE NEW PHYSICS ON THE 1 TEV SCALE

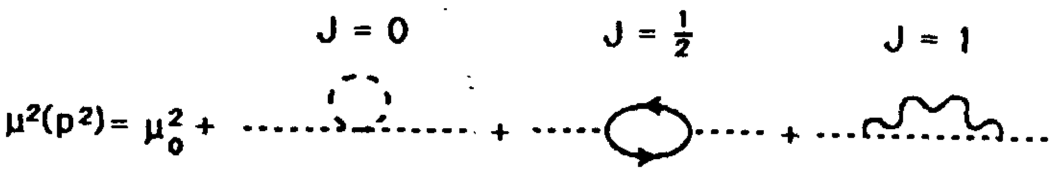
The standard model is incomplete[2]; it does not explain how the scale of electroweak symmetry breaking is maintained in the presence of quantum corrections. The problem of the scalar sector can be summarized neatly as follows.[3] The Higgs potential of the $SU(2)_L \otimes U(1)_Y$ electroweak theory is

$$V(\phi^+\phi) = \mu_0^2\phi^+\phi + |\lambda|(\phi^+\phi)^2 \, . \tag{1}$$

With μ_0^2 chosen less than zero, the electroweak symmetry is spontaneously broken down to the $U(1)$ of electromagnetism, as the scalar field acquires a vacuum expectation value fixed by the low energy phenomenology,

$$<\phi> = \sqrt{-\mu_0^2/2|\lambda|} \equiv (G_F\sqrt{8})^{-1/2} \approx 175 \text{ GeV} \, . \tag{2}$$

Beyond the classical approximation, scalar mass parameters receive quantum corrections involving loops containing particles of spins $J = 1, 1/2$, and 0:



(3)

The loop integrals are potentially divergent. Symbolically, we may summarize the content of Eq. (3) as

$$\mu^2(p^2) = \mu^2(\Lambda^2) + Cg^2\int_{p^2}^{\Lambda^2} dk^2 + \cdots \, , \tag{4}$$

where Λ defines a reference scale at which the value of μ^2 is known, g is the coupling constant of the theory, and C is a constant of proportionality, calculable in any particular theory. Instead of dealing with the relationship between observables and parameters of the Lagrangian, we choose to describe the variation of an observable with the momentum scale. In order for the mass shifts induced by radiative corrections to remain under control (*i.e.*, not to greatly exceed the value measured on the laboratory scale), either

- Λ must be small, so the range of integration is not enormous; or
- new physics must intervene to cut off the integral.

In the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model, the natural reference scale is the Planck mass,

$$\Lambda \sim M_{\text{Planck}} \approx 10^{19} \text{ GeV} . \tag{5}$$

In a unified theory of the strong, weak, and electromagnetic interactions, the natural scale is the unification scale

$$\Lambda \sim M_U \approx 10^{15} \text{ GeV} . \tag{6}$$

Both estimates are very large compared to the scale of electroweak symmetry breaking (2). We are therefore assured that new physics must intervene at an energy of approximately 1 TeV, in order that the shifts in μ^2 not be much larger than (2).

Only a few distinct classes of scenarios for controlling the contribution of the integral in (4) can be envisaged. The supersymmetric solution[4] is especially elegant. Exploiting the fact that fermion loops contribute with an overall minus sign (because of Fermi statistics), supersymmetry balances the contributions of fermion and boson loops. In the limit of unbroken supersymmetry, in which the masses of bosons are degenerate with those of their fermion counterparts, the cancellation is exact:

$$\sum_{i=\substack{\text{fermions}\\ +\text{bosons}}} C_i \int dk^2 = 0 . \tag{7}$$

If the supersymmetry is broken (as it must be in our world), the contribution of the integrals may still be acceptably small if the fermion-boson mass splittings ΔM are not too large. The condition that $g^2 \Delta M^2$ be "small enough" leads to the requirement that superpartner masses be less than about 1 TeV$/c^2$.

A second solution to the problem of the enormous range of integration in (4) is offered by theories of dynamical symmetry breaking such as Technicolor.[5] In of an observable with the momentum scale. In order for the mass shifts induced by radiative corrections to remain under control (*i.e.*, not to greatly exceed the value measured on the laboratory scale), either

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A second solution to the problem of the enormous range of integration in (4) is offered by theories of dynamical symmetry breaking such as Technicolor.[5] In the technicolor scenario, the Higgs boson is composite, and new physics arises on the scale of its binding, $\Lambda_{TC} \simeq O(1 \text{ TeV})$. Thus the effective range of integration is cut off, and mass shifts are under control.

A third possibility, which is appealingly economical but entails the sacrifice of perturbation theory for the electroweak interactions, is that of a strongly interacting gauge sector.[6] This would give rise to WW resonances, multiple production of gauge bosons, and other new phenomena.

Nature may choose any (or none) of these human inventions, but we are driven unavoidably to the conclusion that some new physics must occur on the 1 TeV scale.

3 Reaching the 1 TeV scale

For the reasons we have just outlined, 1 TeV collisions among the elementary constituents become an important landmark. Both general arguments and specific speculations all point to new phenomena and important clues at energies of ~ 0.3-3 TeV. The accelerators now operating or soon to come into operation will thoroughly explore the few hundred GeV regime. The properties of these machines are summarized in Table 1.

To proceed to the 1 TeV scale with useful luminosity, we may contemplate two possibilities:

- An e^+e^- collider with 1 to 3 TeV per beam;

Table 1: Accelerator projects under way

Date	Collisions	Location	$\sqrt{s}$ (TeV)	Mass scale (TeV/c^2)
now	$\bar{p}p$	CERN $S\bar{p}pS$	0.63	~ 0.15
1986	$\bar{p}p$	Fermilab Tevatron	2	~ 0.4
1987	e^+e^-	Stanford SLC	0.1	0.1
1989	e^+e^-	CERN LEP	~ 0.2	~ 0.2
1990	ep	DESY HERA	~ 0.3	~ 0.1

- A $p^{\pm}p$ collider with 10 to 20 TeV per beam.

With current technology, we know how to build a practical hadron supercollider. An electron-positron collider to explore the 1 TeV scale awaits tests of the linear collider concept at the SLC, and the development of efficient, high-gradient acceleration methods. According to the experts, a serious proposal for such a machine is a decade away.[7]

In this context, a number of machines are under discussion for construction or operation in the mid-1990s:

- SSC: the Superconducting Super Collider in the United States, characterized as a 40 TeV proton-proton machine with an instantaneous luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. A conceptual design has recently been submitted to the Department of Energy. Some aspects of it will be reported by Don Stork in the following talk.[8]

- LHC: a Large Hadron Collider in the LEP tunnel could be a 10 to 18 TeV $p^{\pm}p$ device with luminosity in the range of 10^{31-33}, depending on the approach taken. The high energy option requires the development of 10 Tesla magnets, which has obvious appeal for the future.

- CLIC: CERN is also discussing the option of CERN LInear Colliders, now conceived as an e^+e^- facility with $\sqrt{s} = 2$ TeV and a luminosity of 10^{34}.

There is no doubt that the successful demonstration of linear collider principles at SLC will be followed, after appropriate further development, by an Après-SLC proposal.

4 SSC PHYSICS: A FIRST LOOK

The discovery reach of a hadron supercollider is determined by hard scattering processes in which the constituents interact at high energies, as depicted in Fig. 2. Cross sections may be calculated in the renormalization group improved parton model, provided we know the behavior of the quark and gluon distributions within the proton as functions of x and Q^2. For the parton subprocesses

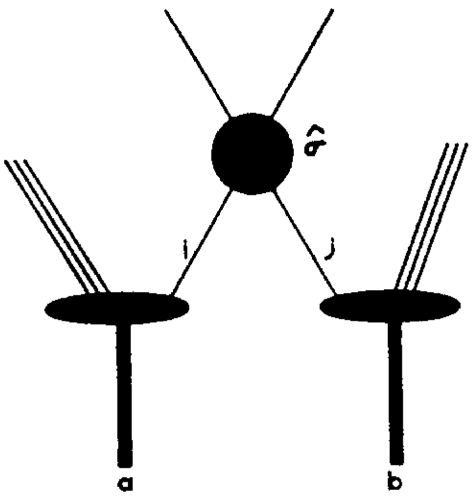

Figure 2: Parton-model representation of a hard-scattering event.

of interest, the range over which the structure functions must be known is

$$(10\ \mathrm{GeV})^2 \lesssim Q^2 \lesssim (10^4\ \mathrm{GeV})^2, \tag{8}$$

which may correspond to $\langle x\rangle$ as small as 10^{-4}. With the parton distributions written as $f_i^{(a)}(x, Q^2)$ for the number density of partons of species i in hadron a, hadronic cross sections are given schematically by

$$\begin{aligned} d\sigma(a+b\to c+X) &= \sum_{ij}\int dx_a dx_b \cdot \\ & \qquad f_i^{(a)}(x_a,Q^2) f_j^{(b)}(x_b,Q^2) d\hat{\sigma}(i+j\to c+X), \end{aligned} \tag{9}$$

where $d\hat{\sigma}$ represents the elementary cross section. Structure functions suitable for the extrapolation to supercollider energies are available,[9] and the parton-level cross sections are known for a great many reactions of potential interest.

One indication that the parton-model procedure is sound, and that knowledge of the structure functions derived from experiments on deeply inelastic lepton scattering is adequate, is provided by $S\bar{p}pS$ data on hadron jets. Figure 3 shows representative data from the UA-1 Collaboration[10] on the inclusive jet cross section $d\sigma/dp_\perp dy\,|_{y=0}$, compared with the predictions of the QCD Born term. The agreement is quite satisfactory.[11]

Thus satisfied with the reasonableness of our procedure, we may make the extrapolation to supercollider energies. A useful way to display the results is to

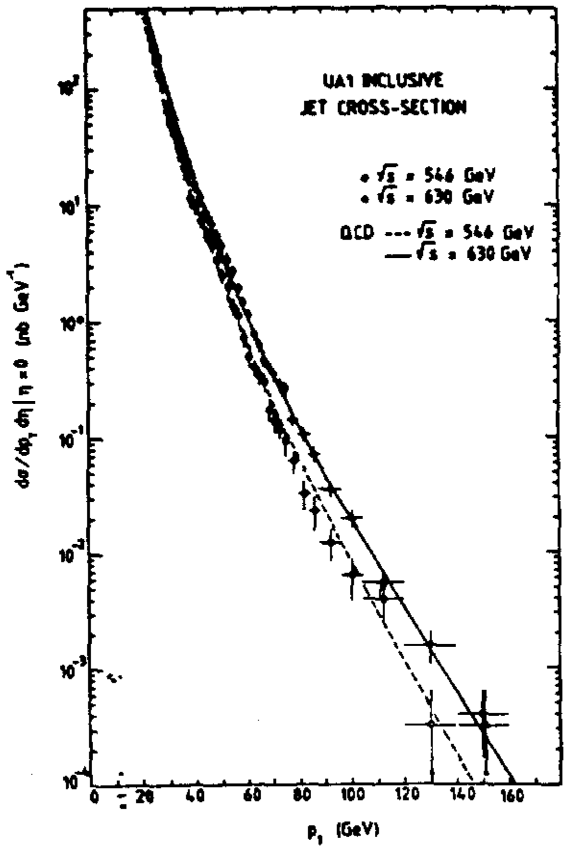

Figure 3: The inclusive jet cross section for the pseudorapidity interval $|\eta| < 0.7$, as a function of the jet transverse momentum, as measured by the UA-1 Collaboration. The open dots correspond to the data at $\sqrt{s} = 546$ GeV and the solid dots to those at $\sqrt{s} = 630$ GeV.

examine the trigger rate for events with transverse energy E_T greater than some threshold E_T^{min}. This is shown in Fig. 4 for the nominal operating conditions of the SSC: $\sqrt{s} = 40$ TeV and $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1}, as well as at 10 and 100 TeV. At 40 TeV, a "high-E_T" trigger with threshold set at 2 TeV will count at 1 Hz from two-jet QCD events. This is of interest in planning triggers which will efficiently select "interesting" events from the $2 \cdot 10^8$ interactions which will take place each second in an SSC interaction region.

5 Electroweak physics

The principal standard model issues to be addressed with a multi-TeV hadron collider are these:

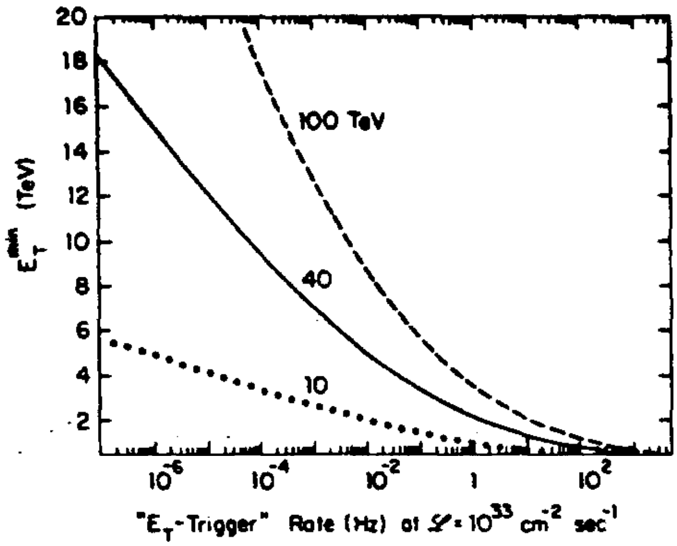

Figure 4: Counting rate for an E_T-trigger in pp collisions at an instantaneous luminosity of $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1} (after *EHLQ*). The threshold is defined for transverse energy deposited in the central region of rapidity, defined by $|y_i| < 2.5$ for jets 1 and 2.

- The rate of $W^{\pm}$ and Z^0 production. This is chiefly of interest for investigations of the production mechanism itself and for the study of rare decays of the intermediate bosons. We expect that by the time a supercollider comes into operation the more basic measurements such as precise determinations of the masses and widths of the intermediate bosons will have been accomplished.

- The cross section for pair production of gauge bosons. These are sensitive to the structure of the trilinear couplings among gauge bosons, and must be understood as potential backgrounds to the observation of heavy Higgs bosons, composite scalars, and other novel phenomena.

- The Higgs boson itself. In the minimal electroweak model, this is the lone boson remaining to be found. Elucidating the structure of the Higgs sector (and mot merely finding a single Higgs scalar) is one of the primary goals of experimentation in the TeV regime.

Let us take a moment to look briefly at each of these points.

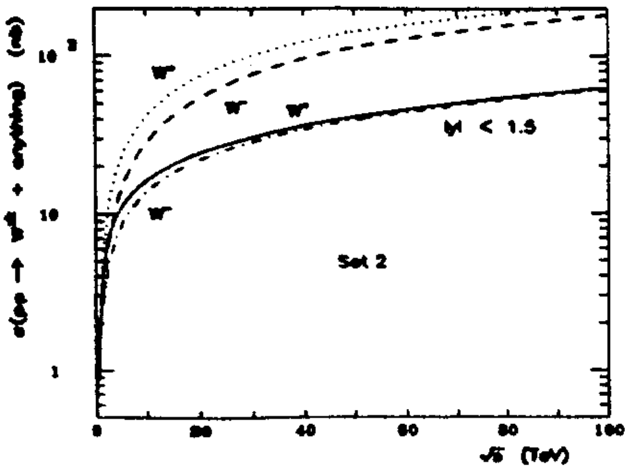

Figure .5: Cross sections for $W^\pm$ production in pp collisions in the Drell-Yan picture, integrated over all rapidities, and restricted to the interval $|y| < 1.5$ (after *EHLQ*).

The integrated cross sections for W^+ and W^- production in pp collisions are shown in Fig. 5 as functions of the c.m. energy $\sqrt{s}$. Also shown are the cross sections for production of $W^\pm$ in the rapidity interval $-1.5 < y < 1.5$. The number of intermediate bosons produced at a high-luminosity supercollider is impressively large. At 40 TeV, for example, a run with an integrated luminosity of 10^{40} cm^{-2} would yield approximately $6 \cdot 10^8$ Z^0s and $2 \cdot 10^9$ $W^\pm$s. For comparison, at a high-luminosity Z^0 factory such as LEP ($\mathcal{L} \simeq 2 \cdot 10^{31}$ cm^{-2}sec^{-1}) the number of Z^0s expected in a year of running is approximately 10^7. There is no competitive source of *charged* intermediate bosons.

The angular distribution of the produced intermediate bosons is of great importance for the design of experiments. At supercollider energies, many intermediate bosons will be produced within a narrow cone about the beam direction. In a 40 TeV machine with an average luminosity of 10^{33}, there will be a flux of about 10 W^+/second emitted within 2° of the beam direction, in each hemisphere. Special purpose detectors deployed near the forward direction may thus have significant advantages for the study of rare decays.

There are many reasons to be open to the possibility of new gauge bosons:

- **High energy parity restoration in an $SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$ electroweak gauge theory;**
- **The occurrence of extra $U(1)$ gauge symmetries, implying additional Z^0s, for example in unification groups larger than $SU(5)$;**
- **The low-energy gauge groups emerging from superstring models.[12]**

In a specific theory, the style of calculation just described leads to an estimate of the cross section for the production of new gauge bosons. As an example, I show in Fig. 6 the cross section for production of a new W-boson with standard gauge couplings to the light quarks. For the 40 TeV energy projected for the SSC, we may anticipate sensitive searches out to a mass of about 6 TeV/c^2.

Incisive tests of the structure of the electroweak interactions may be achieved in detailed measurements of the cross sections for the production of W^+W^-,

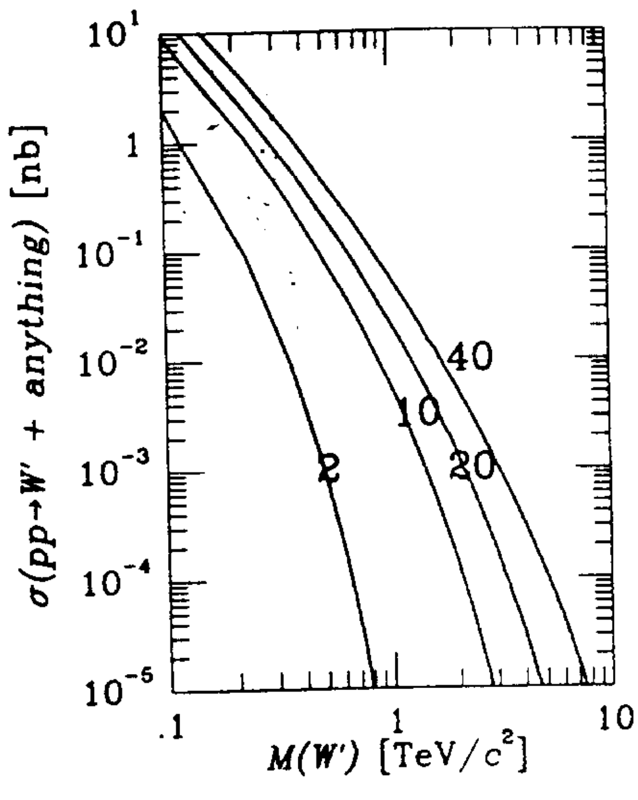

Figure 6: Cross section for the production of a heavy W-boson with rapidity $|y| < 1.5$ in pp collisions at 2, 10, 20, and 40 TeV (after *EHLQ*).

$W^\pm Z^0$, Z^0Z^0, $W^\pm\gamma$, and $Z^0\gamma$ pairs. The rate for $W^\pm\gamma$ production is sensitive to the magnetic moment of the intermediate boson. In the standard model there are important cancellations in the amplitudes for W^+W^- and $W^\pm Z^0$ production which rely on the gauge structure of the WWZ trilinear coupling. The Z^0Z^0 and $Z^0\gamma$ reactions do not probe trilinear gauge couplings in the standard model, but are sensitive to nonstandard interactions such as might arise if the gauge bosons were composite. In addition, the W^+W^- and Z^0Z^0 final states may be significant backgrounds to the detection of heavy Higgs bosons and possible new degrees of freedom.

The intrinsic interest in the process $q_i\bar{q}_i \to W^+W^-$, which accounts in part for plans to study e^+e^- annihilations at c.m. energies around 180 GeV at LEP, is owed to the sensitivity of the cross section to the interplay among the γ-, Z^0-, and quark-exchange contributions. As is well known, in the absence of the Z^0-exchange term, the cross section for production of a pair of longitudinally polarized intermediate bosons is proportional to $\hat{s}$, in gross violation of unitarity. It is important to verify that the amplitude is damped as expected. The mass spectrum of W^+W^- pairs is of interest both for the verification of gauge cancellations and for the assessment of backgrounds to heavy Higgs boson decays.

At this point, it is worth recalling why there must be a physical Higgs boson, or something very similar, in any satisfactory electroweak theory. To do so, let us consider the role of the Higgs boson in the cancellation of high-energy divergences. An illuminating example is provided by the reaction

$$e^+e^- \to W^+W^-, \tag{10}$$

which is described in lowest order in the Weinberg-Salam theory by the four Feynman graphs in Fig. 7. The leading divergence in the $J = 1$ amplitude of the neutrino-exchange diagram in Fig. 7(a) is cancelled by the contributions of the direct-channel γ- and Z^0-exchange diagrams. However, the $J = 0$ scattering amplitude, which exists in this case because the electrons are massive and may therefore be found in the "wrong" helicity state, grows as $s^{1/2}$ for the production of longitudinally polarized gauge bosons. The resulting divergence is precisely cancelled by the Higgs boson graph of Fig. 7(d). If the Higgs boson did not exist, we should have to invent something very much like it. From the point of view of S-matrix theory, the Higgs-electron-electron coupling must be proportional to

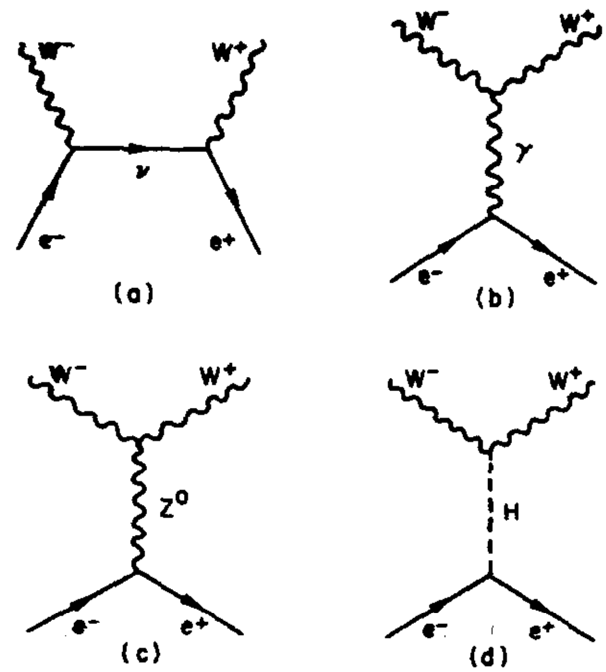

Figure 7: Lowest-order contributions to the reaction $e^+e^- \rightarrow W^+W^-$ in the standard model.

the electron mass, because "wrong helicity" amplitudes are always proportional to the fermion mass.

Without spontaneous symmetry breaking in the standard model, there would be no Higgs boson, no longitudinal gauge bosons, and no extreme divergence difficulties. (Nor would there be a viable low-energy phenomenology of the weak interactions.) The most severe divergences are eliminated by the gauge structure of the couplings among gauge bosons and leptons. A lesser, but still potentially fatal, divergence arises because the electron has acquired mass – because of the Higgs mechanism. Spontaneous symmetry breaking provides its own cure by supplying a Higgs boson to remove the last divergence. A similar interplay and compensation must exist in any satisfactory theory.

6 SUPERSYMMETRY AT THE SSC

As an illustration of the capability of the SSC to search for phenomena beyond the standard model, let us consider one example from supersymmetry. In a supersymmetric theory, particles fall into multiplets which are representations of the supersymmetry algebra. Superpartners share all quantum numbers except spin; if the supersymmetry is unbroken, they are degenerate in mass. The number of fermion states (counted as degrees of freedom) is identical with the number of boson states. By examining the quantum numbers of the known particles, we readily see that there are no candidates for supersymmetric pairs among them. Supersymmetry therefore means doubling the particle spectrum, compared with the standard model. In fact, we must expand the spectrum slightly further, because the minimal supersymmetric extension of the standard model requires at least two doublets of Higgs bosons. The interactions among old and new particles are prescribed by the supersymmetric extension of the usual interaction Lagrangian, which we shall take to be the $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$ theory. If supersymmetry is an invariance of the Lagrangian, it is evidently a broken symmetry, because observationally boson masses are not equal to the masses of their fermion counterparts. For supersymmetry to resolve the hierarchy problem, we have seen in §2 that it must be *effectively* unbroken above the electroweak scale of $O(1\text{ TeV})$. This suggests that the superpartner masses will themselves be $\lesssim 1\text{ TeV}/c^2$.

The outlines of the search for supersymmetry at the SSC are given in *EHLQ*.[2] Progress since Snowmass '84 was summarized recently at the Oregon workshop by Dawson.[13] Cross sections for the production of superpartners will be quite ample for a luminosity of $10^{32}\text{ cm}^{-2}\text{sec}^{-1}$ or more, and a c.m. energy of 40 TeV. As an example, I show in Fig. 8 the integrated cross section for the production of gluinos with rapidities $|y_i| < 1.5$, in the reaction

$$pp \to \tilde{g}\tilde{g} + \text{anything}. \tag{11}$$

On the basis of these and other cross sections and a rudimentary assessment of the requirements for detection, we have estimated the discovery limits for various energies and luminosities. The estimates for gluinos are shown in Fig. 9. Consideration of similar curves for the whole range of conjectured superpartners leads to the judgment that a supercollider like the SSC will be adequate to establish the presence or absence of the superpartners predicted by models of low-energy supersymmetry.

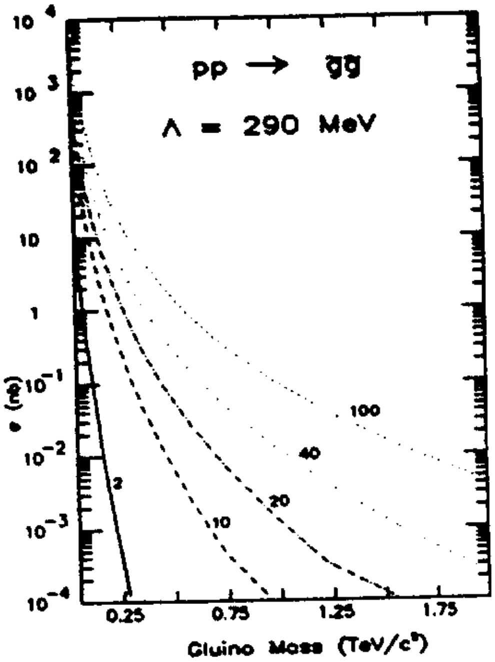

Figure 8: Cross sections for the reaction $pp \rightarrow \tilde{g}\tilde{g}$ + anything as a function of gluino mass, for collider energies $\sqrt{s} = 2, 10, 20, 40$, and 100 TeV. Both gluinos are restricted to the interval $|y_i| < 1.5$. For this illustration, the squark mass is set equal to the gluino mass. [From *EHLQ*, Ref. 2.]

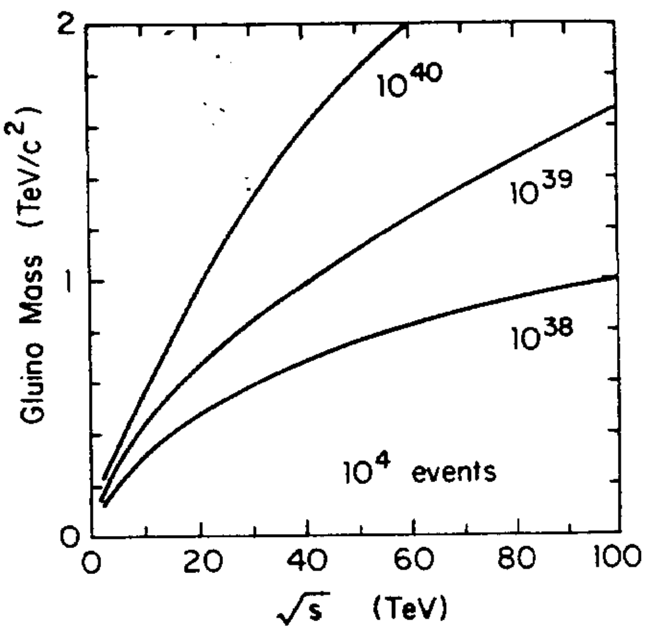

Figure 9: "Discovery limits" for gluinos in pp and $\bar{p}p$ collisions. Contours show the largest mass for which 10^4 gluino pairs are produced with $|y_i| < 1.5$, for specified energy and luminosity.

7 Concluding Remarks

In this brief survey, it has been possible only to scratch the surface of the physics opportunities presented by a high-energy, high-luminosity hadron collider. The examples we have considered here do begin to indicate the scope of physics issues to be addressed, ranging from detailed study of known particles, such as the intermediate bosons, to the search for high-mass exotica. The comprehensive studies of physics possibilities carried out over the past three years have shown convincingly that

> A 40 TeV collider which permits experimentation at integrated luminosities of at least 10^{39} cm^{-2} will make possible detailed exploration of the 1 TeV scale.

This conclusion is based on detailed consideration of the canonical inventions intended to improve the standard model, technicolor and supersymmetry, and of the standard model itself. In addition, there are many opportunities for exploring constituent interactions at subenergies up to about 10 TeV in the study of jets, the search for additional gauge bosons, *etc.* "Fixed-target style" colliding beams experiments may be well suited to address rare W decays and heavy flavor physics, for example. The SSC is not by any means a one-issue facility, and it is important that we mount a diversity of experimental initiatives, to realize its full scientific potential.

With respect to experimentation at the SSC, there are a few detector issues which I like to raise at every opportunity.

- The utility of high-efficiency W and Z detectors. The discovery physics we have considered in assessing the physics prospects of the SSC can all be done by relying upon the leptonic decays of the gauge bosons, but we can move to a deeper level of experimentation by learning to use the nonleptonic decays as well.

- The UA-1 experiment has already indicated the value of "hermetic" detectors, which can capture and measure all the visible energy emitted in the central region. For a general-purpose SSC detector, it is of interest to require hermeticity for rapidities $|y| < 3$.

- **Examples from technicolor and the Higgs sector of the standard model indicate that good-efficiency $\tau, b, \ldots$ tags will be of considerable value in enhancing signals over background. Full utilization of the heavy flavor tag requires measuring the four-momenta of the short-lived particles as well.**

- How to reduce the interaction rate of $\sim 10^8$ Hz to the $O(1\ \text{Hz})$ rate at which complex events can be written on storage media (magnetic tapes, optical discs)? There are many opportunities for creativity here!

- Bringing remote local intelligence into the detector components themselves requires the implementation of radiation-hardened electronics, especially near the beam directions.

We are faced with great opportunities![14]

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It is a pleasure to thank our hosts Bob Panvini and Tom Weiler and their colleagues for assembling a stimulating scientific program, and for seeing to it that our stay in Nashville was again a pleasant and interesting one. Fermilab is operated by Universities Research Association, Inc., under contract with the United States Department of Energy.

FOOTNOTES AND REFERENCES

[1] P. Ramond, *These Proceedings*, p. .

[2] For a summary of the standard shortcomings, see E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, *Rev. Mod. Phys.* **56**, 579 (1984).

[3] M. Veltman, *Acta Phys. Polon.* *B*12, 437 (1981); C. H. Llewellyn Smith, *Phys. Rep.* **105**, 53 (1984).

[4] Some recent reviews of the experimental implications of supersymmetry on the scale of electroweak symmetry breaking appear in D. V. Nanopoulos and A. Savoy-Navarro (Editors), *Phys. Rep.* **105**, 1 (1984); H. E. Haber and G. L. Kane, *ibid.* **117**, 75 (1985); S. Dawson, E. Eichten, and C. Quigg, *Phys. Rev.* *D*31, 1581 (1985); R. M. Barnett, H. E. Haber, and G. L. Kane, *Nucl. Phys.* **B267**, 625 (1986).

[5] For reviews of the technicolor idea, see E. Farhi and L. Susskind, *Phys. Rep.* **74**, 277 (1981); R. Kaul, *Rev. Mod. Phys.* **55**, 449 (1983). A recent study for the current generation of accelerators appears in E. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, Fermilab-Pub-85/145-T, *Phys. Rev. D*, (to be published).

[6] The idea of a strongly interacting gauge sector is an evergreen in particle theory. In the context of the standard model, an early discussion appears in B. W. Lee, C. Quigg, and H. B. Thacker, *Phys. Rev.* *D*16, 1519 (1977); see also M. Veltman, *Acta Phys. Polon.* *B*8, 475 (1977). Recent investigations appropriate to the supercollider scale are reported in M. Chanowitz and M. K. Gaillard, *Nucl. Phys.* **B261**, 379 (1985); *Phys. Lett.* **142B**, 85 (1984).

[7] *Report of the HEPAP Subpanel on Advanced Accelerator R&D and the SSC*, U. S. Department of Energy Report DOE/ER-0255 (December, 1985).

[8] D. Stork, *These Proceedings*, p. .

[9] Structure functions for supercollider physics are given by Eichten, *et al.*, Ref. 2, and by D. W. Duke and J. F. Owens, *Phys. Rev.* *D*30, 49 (1984).

[10] G. Arnison, *et al.* (UA-1 Collaboration), CERN-EP/86-29.

[11] The curves shown are 1.5× the lowest-order QCD predictions, evaluated with $Q^2 = p_\perp^2$. The systematic errors on the data are ±70%. Theoretical uncertainties are of a similar magnitude, but tend to increase the predicted cross section. These are discussed by Eichten, *et al.*, Ref. 2, and by R. K. Ellis and J. C. Sexton, Fermilab-Pub-85/152-T.

[12] See, for example, V. Barger, *These Proceedings,* p. .

[13] S. Dawson, in *Supercollider Physics,* edited by D. E. Soper (World Scientific, Singapore, 1986), p. 171.

[14] Basic references on supercollider physics include the following: *EHLQ*, Ref. 2; *Proceedings of the 1984 Summer Study on Design and Utilization of the Superconducting Super Collider,* edited by R. Donaldson and J. G. Morfín (Fermilab, Batavia, Illinois, 1984); *Large Hadron Collider in the LEP Tunnel,* edited by G. Brianti, *et al.*, CERN 84-10; *Proceedings of the Workshop on Electroweak Symmetry Breaking,* edited by T. Appelquist, M. K. Gaillard, and I. Hinchliffe, LBL-18571; *$\bar{p}p$ Options for the Supercollider,* edited by J. E. Pilcher and A. R. White (University of Chicago, 1984); *Physics at the Superconducting Super Collider Summary Report,* edited by P. Hale and B. Winstein (Fermilab, 1984); *Supercollider Physics,* edited by D. E. Soper (World Scientific, Singapore, 1986).